TEN YEAR CHANGE IN FOREST SUCCESSION AND COMPOSITION MEASURED BY REMOTE SENSING

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Abstract

Vegetation dynamics and changes in ecological patterns were measured by remote sensing over a 10-year period (1973-1983) for 148,406 landscape elements, covering more than 500 km² in a protected forested wilderness. Quantitative measurements were made possible by new methods to detect ecologically meaningful landscape units; these allowed measurement of ecological transition frequencies and calculation of expected recurrence times. Measured ecological transition frequencies reveal boreal forest wilderness as spatially heterogeneous and highly dynamic, with one-sixth of the area in clearings and early successional

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stages, consistent with recent postulates about the spatial and temporal patterns of natural ecosystems. Differences between managed forest areas and a protected wilderness allow assessment of different management regimes.

I.Introduction and Overview

Some classic questions in ecology concern patterns of vegetation in space and time. The old idea that a natural, undisturbed landscape would be composed of a single, "climax" state, spatially homogenous and temporally permanent, has been largely rejected since the early 1970's. Newer interpretations suggest that a naturally vegetated landscape forms a rich mosaic pattern.[1] However, There have been few sources of data to test hypotheses about vegetation patterns at regional scales. Ground-based sampling cannot provide adequate data on landscape patterns for large areas[2]. With the advent of satellite remote sensing, advances in the digital image processing, and improved understanding of the interactions of light with vegetation, studies of pattern at local, regional, and global scales for periods dating from the 1972 launch of Landsat 1 are possible. This potential has not been well exploited; applications of remotely sensed data have focused on single time-frames or changes over one to three years, and on taxonomic rather than ecologically functional classifications[3].

Both measuring vegetation patterns and understanding the causes of these patterns are difficult because vegetation composition responds to diverse influences operating at many scales. For example, effects of fire, wind, insects and disease persist for years to centuries and extend over meters to kilometers as the vegetation undergoes ecological succession.

Knowledge of vegetation patterns is critical to many important scientific issues. As an example, in the study of the biosphere, vegetation patterns and changes in these patterns can influence regional and global climate through effects on energy exchange, evaporation of water, and chemical cycling[4].

We report an innovative use of high-resolution satellite imagery for interpretation of vegetation dynamics and patterns for a forested region over for a ten year interval. This quantitative method makes possible the examination of long-standing ecological questions.

II. Methods

The study is of the protected wilderness of the Boundary Waters Canoe Area and adjacent, multiple use, Superior National Forest in northeastern Minnesota. Boreal forests dominate the area; the most important species are aspen, jack pine, balsam fir and spruce, whose relative abundance varies with environment and

successional stage. A boreal forest was chosen because of the great extent and importance of this biome, and its relative taxonomic simplicity.

We acquired 1973 Landsat 1 and 1983 Landsat 4 multispectral scanner (MSS) data for early summer dates. An ecological classification of the two scenes was developed as follows: One hundred and fifty "training sites" were assigned to ecological classes defined by successional state and environmental constraints on the basis of ground sampling and air-photo interpretation. Next, spectral data of the same kind as obtained from the sensor on Landsat 4, but with higher spatial resolution were obtained for these sites from aircraft borne sensors. These were used to define spectral classes that corresponded to the classes determined from the ground sites. These spectral classes were then applied to the 1983 Landsat MSS imagery of the study area; means and variances were calculated for this imagery for each ecological class, thus defining multispectral signatures. Equivalent multispectral signatures were calculated for the 1973 MSS data by using the 1983 classification and transforms to account for sensor and atmospheric differences. In each scene, each pixel was assigned to an ecological class using a hybrid parallelpiped classifier[5].

Frequencies of changes between ecological classes from 1973 to 1983 were determined and conditional transition probabilities between classes were calculated. The class frequencies and

transition probabilities are statistical estimates of the actual values. Differences between the 1973 and 1983 images primarily reflect changes in vegetation but it should be recognized that there are several other potential sources of differences: different sensors, different atmospheric conditions, incomplete congruence of pixels, mislocation of training site on the images, and phenological differences. We attempted to control for most of these before comparing images. Changes due to sensors and atmosphere are linear and were corrected by comparing reflectances of well-defined water and high-reflectance areas. Phenological differences were corrected by using the reflectance of bog areas, under the assumption that this reflectance was the result solely of phenological differences in the two years. Some displacement of pixels in the two images unavoidably changes reflectances where edges of patches are encountered; this could be especially significant due to heterogeneity of the study area, and may be reflected in narrow (single-pixel) bands of changed pixels along the shores of several lakes and other edges. Changes in sensor resolution may have similar effects. The spectral signatures of classes have been defined from examples; overlap with other non-sampled ecological types cannot be excluded.

When the accuracy of classification of the 1983 ground samples was evaluated, correct classification was 84% overall, varying from 75% to 100% for the individual classes. Thus, while the ecological identification of each class is substantially

accurate, an element of caution is necessary in giving ecological interpretations to low frequency transitions.

In previous studies, spectral classes have usually been defined only in terms of species composition rather than explicitly as ecological states[6 7]. Five classes were separable in both 1973 and 1983 MSS data: (1) clearings with low sparse vegetation; (2) regenerating broadleaf; (3) broadleaf (primarily aspen); (4) mixed conifer and broadleaf and (5) closed conifer (black spruce, jack pine, or upland spruces and balsam fir). Regeneration and mixed broadleaf/conifer classes include open bogs and clearings which may be stable over time. In terms of these classes, there are two typical successional sequences: (1) clearings to regeneration to broadleaf to mixed and conifer classes; (2) clearings to regeneration to conifer class (primarily to spruce). Fire is the dominant natural disturbance initiating succession; windthrows, insect outbreaks, and drought are also important. Logging is an important anthropogenic disturbance outside of the protected wilderness where no logging has occurred since the 1940's.

III. Results and Discussion

The Boundary Waters Canoe Area wilderness shows great spatial heterogeneity in both years, and in the patterns of change between the years. This can be seen in Fig 1, where it is evident that a large proportion of pixels border pixels of

another class. For example, areas vegetated in 1973 that were devegetated and appear as clearings in 1983 are widely scattered in small clusters except in logged areas outside of the wilderness; areas that were clearings in 1973 and entered the regeneration class in 1983 are similarly widely scattered except for a concentration primarily in the non-wilderness portion due to a major 1971 fire.

The protected wilderness has appears temporally dynamic, as suggested by the occurrence of approximately 15% of the land area in early successional vegetation (clearings and regeneration classes) (Table 1). However, the proportions of the landscape in each class are the result of net transitions in and out of the class, and are not alone necessarily a good index of the dynamic characteristics of a landscape. The transition matrix [Table 2] shows direct measures of rates of change among classes. Each diagonal element in the transition matrix is a <u>retention frequency,</u> the proportion of landscape elements in one class which remained in the same class between 1973 and 1983. Each off-diagonal element is a <u>transition frequency</u>, the rate at which units in a given class change other states during the ten-year period. Retention frequencies are clues to stability, while dynamics are captured in the transition frequencies.

The transition' matrix indicates that the wilderness forest is highly dynamic; even the late successional classes have a retention frequency less than 60% (Fig 2a; Table 2A). The

retention frequency increases with the successional stage, with clearings having the lowest retention frequency (17%). This is consistent with the slower turnover expected in late successional stages.

The highest state-to-state transition frequencies are clearings to regeneration, and aspen to mixed broadleaf-conifer, both of which exceed 45%; these transition are consistent with typical successional trends.

Disturbance transitions (from later to earlier successional stages) generally are generally low; the transition from mixed stands to clearings is less than 1%; from conifers to clearings about 1%.

Comparison of transition probabilities inside and outside of the protected wilderness provides a quantitative measurement of effects of recent human activities in the Superior National Forest on landscape patterns. Disturbances, indicated by transitions from mature forested types to clearing and regeneration, are five to ten times higher in the non-wilderness than in the protected wilderness and are concentrated in logged areas (Fig 2B; Table 2B). This comparative measurement could be used widely to provide a quantitative assessment of the effects of human-induced disturbance on the landscape.

The transition matrix is consistent with qualitative ecological expectations about succession, and in this way serves to confirm the remote sensing methodology as applied here.

April 15, 1987

Consequently, our results appear reliable as a quantitative measure of successional rates never available before over a large area or for a large number of landscape elements. The high transition probabilities suggest that landscape elements are far from constant over time.

From these data it is possible to calculate a static steady-state expected condition of the forest and also to calculate the average expected recurrence time, which is the expected time for a landscape element to return to a given state once it has left that state[8]. The expected steady-state conditions, assuming that the transition probabilities observed between 1973 and 1983 are time invariant, are: 1.5% of the pixels would be in clearings; 11% in regenerating; 14.5% in aspen, 43.3% in mixed; and 29.3% in conifer. It is interesting that the observed present proportions of the landscape are not greatly different from the projected steady-state (Table 1); the percentage in aspen is higher than at steady-state and the proportion in the mixed and conifer classes are slightly lower. This indicates that the calculated steady-state would have a temporal dynamic similar to the present forest.

Studies of the Superior National Forest and similar boreal forests suggest that prior to European settlement each area on the landscape burned on the average once a century[9]. The recurrence time can be estimated for our study area by calculating the steady-state transition probabilities from the

measured transition matrix (Table 3), assuming the process is Markovian[10]. The calculated average recurrence times within the protected wilderness is 803 years for clearings rather than the 100 years estimated from historical studies of the vegetation (Table 3). This difference reflects at least in part the impact of intentional fire suppression in the 20th century. To our knowledge, this is the first calculation of recurrence times based on quantitative measurement for a large area. The impact of recent human activities including logging is suggested by differences in clearing and regeneration classes recurrence times inside and outside of the wilderness. The recurrence times for clearings and regenerating vegetation is much shorter in the non-wilderness sample area, where fires have occurred recently and logged is permitted, than in the protected wilderness. In contrast, the recurrence times of later successional stages inside and out of the protected wilderness are similar.

IV. Conclusions

Remote sensing has permitted the first quantitative analysis of regional forest dynamics over a ten year period, revealing a boreal forest test area as heterogenous at several scales, and as dynamic over time. Considerable successional change is observed over a single decade, and there are considerable changes in the overall areal proportions of the landscape in early successional

stages. These results conform to newer interpretations in vegetation ecology which perceive a naturally vegetated landscape as rich mosaics, with each landscape unit undergoing changes in state over time.

These results strongly indicate that remote sensing can be used to measure ecosystem dynamics and landscape patterns, especially through the use of the state transition matrix. While our study utilized a boreal forest and a ten-year observation period with Landsat MSS data, the technique can be extended to any ecosystem, satellite sensor and observation frequency. This approach provides a means for synthesis of ecological patterns at various temporal and spatial scales; in the work reported here, ground observations for single dates at scales of a few square meters were linked to remote sensing at regional scales over a decade. There is no reason to doubt that these same techniques could be extended to synoptic scales and periods far beyond the 10 years of this study as Landsat and similar data become available.

The new method has many applications. For example, in spite of a growing recognition of the dynamic character of landscapes, vegetation is frequently mapped as large, homogeneous patches[11]. Our approach permits mapping of actual patterns, rather than the generalized patterns of traditional and "potential" vegetation maps. Further experiments, involving sensors of different resolution or combined pixels, will allow more detailed analysis

of the spatial and dynamic nature of ecosystems. Comparisons of areas under differing management further demonstrate a capability for quantitative description of landscapes and comparison of management schemes. We expect extensive applications will be developed in further research[12].

April 15, 1987

FIGURE 1 10 yr (1973-1983) forest dynamics as detected by LANDSAT imagery for a portion of the study area. This image shows elements that changed from clearings in 1973 to regeneration in 1983 (red), and elements that changed were vegetation in 1973 and were deforested to clearings (yellow). Blue landscape elements did not change class. Light blue boundaries distinguish the Boundary Waters Canoe Area protected wilderness (upper and lower portions of scene) from non-wilderness areas. White areas are clouds. Dark blue areas are lakes and cloud shadows. The landscape is revealed as heterogenous; even a burned area (upper right) is patchy in its changes during the decade. Logging and other anthropogenic activities results in a higher rate of disturbances in the non-wilderness area.

FIGURE 2. Ecological Transition diagram for (a) 148,406 landscape elements in the protected wilderness of the Boundary Waters Canoe area; and (b) 113,738 landscape elements in a comparable area in the contiguous Superior National Forest.

NOTES:

1. Whittaker, R.H. and S.A. Levin. Theor. Popul. Biol. 12:117 (1977); Risser, P.G., J.R.Karr, and R.T.T.Forman. Illinois Natural History Survey Special Publication No.2 (Champaign, Ill, 1984); R.T.T.Forman and M.Godron Landscape Ecology (John Wiley and Sons, N.Y. 1986); Watt, A.S., J. Ecol. 31:1 (1947).

2. See for example the methodology employed by J.S. Olson, J.A.Watts, L.J.Allison. Oak Ridge National Lab. Pub. # ORNL-5862 (1983);see also H.Lieth and R.H.Whittaker (eds.) Primary Productivity of the Biosphere (Springer Verlag, N.Y., 1975).

3. See, for example: R.F. Nelson, R.S. Latty, G. Mott, Photogramm. Engng. and remote Sensing 50:607 (1984); S.N. Goward, C.J. Tucker, D.G. Dye, Vegetatio 64:3 (1985); C.J. Tucker, J.R.G. Townshend, T.E. Goff, Sciences 227:369 (1985); J. Franklin, T.L. Logan, C.E. Woodcock, A.H. Strahler. 1986. I.E.E.E. Trans. Geosci. remote Sensing 24:139 (1986); J.R.G. Townshend, C.O. Justice, Int. J. remote Sensing 7:1435 (1986).

4. D.B.Botkin, J.E. Estes, R.M. MacDonald, M.V. Wilson. Bioscience 34,508 (1984); R.H.Waring, J.D.Aber, J.M.Melillo, B.Moore III, BioScience 36,433 (1986); R.H.Whittaker and G.E.Likens Human Ecology 1,301 (1973).

5. 1983 data were from Landsat 4, with picture elements (pixels) 60x60 m. 1973 data, from Landsat 1, are 80 x 80 m. pixels, but data were resampled to Landsat 4 pixel size. Additional classes were separable in the 1983 image because of the higher Landsat 4 spatial resolution, but could not be used in this study.

6. Ground observations included: 1) 98 plots (60 m diameter) described by standard vegetation sampling and concentrated in forested areas and stands dominated by aspen and black spruce; 2) 50 additional training areas were selected on the basis of extensive field experience by one of us (KW) from interpretation of aerial photography and high-resolution (ca. 12 m pixel size) imagery from an aircraft-borne scanner. See D.B.Botkin, J.E.

Estes, R.M. MacDonald, M.V. Wilson. Bioscience 34,508 (1984).

7. Class separability appeared due to differences in (1) leaf optical properties; (2) vegetation cover; and (3) proportions of conifers and broadleaf species.

8. See for example Botkin, D.B. and M.J.Sobel, Amer. Nat.<u>109</u>, 625 (1975).

9. Heinselman, M., J. Quartern. Res.<u>3</u>:329 (1973); Laframboise, P. Soc. Devel. Baie James, Rapport d-etape (1975); Gerardin, V., Envron. Can. and Soc. de devel. Baise=Jaems (1980); Lafond, A. and G. Ladouceur. Nat. Canad. 95:317 (1968); Boudoux, M. Serv. Canad. de for., Min. des terres et forets, Quebec (1978); Cogbill, C.V. <u>Analysis of Vegetation, Environment, and Dynamics in the boreal forests of the Laurentian highlands, Quebec</u>. Ph.D. thesis, Univ. Toronto (1982).

10. The recurrence time was calculated as (1 - P'_j)/ (P'_j(1-P_{jj}) where P'_j is the steady-state Markovian transition probability and P_{jj} is the measured retention probability. For consideration of Markov Processes in the analysis of ecological succession, see J.M. Emlen <u>Population Biology</u> MacMillion,N.Y. (1985). In general, forest succession is non-Markovian; the utility of this calculation is the implication concerning expected recurrence times. We thank D. Woodby for these calculations.

11. For example, see: A.W. Kuchler, Potential Natural Vegetation of the Coterminous United States (American Geographical Society, New York; 1966).

12. The research was supported by several grants from NASA to the University of California, Santa Barbara, as part of cooperative research agreements with Johnson Space Center and Goddard Space Flight Center. Analytical work reported here was conducted by Science Applications Research under contract with Goddard Space Flight Center. We wish to thank the staff of the Superior National Forest for their extensive cooperation and assistance. We also thank R.A.MacDonald of NASA for his contributions to the research and to the concepts.

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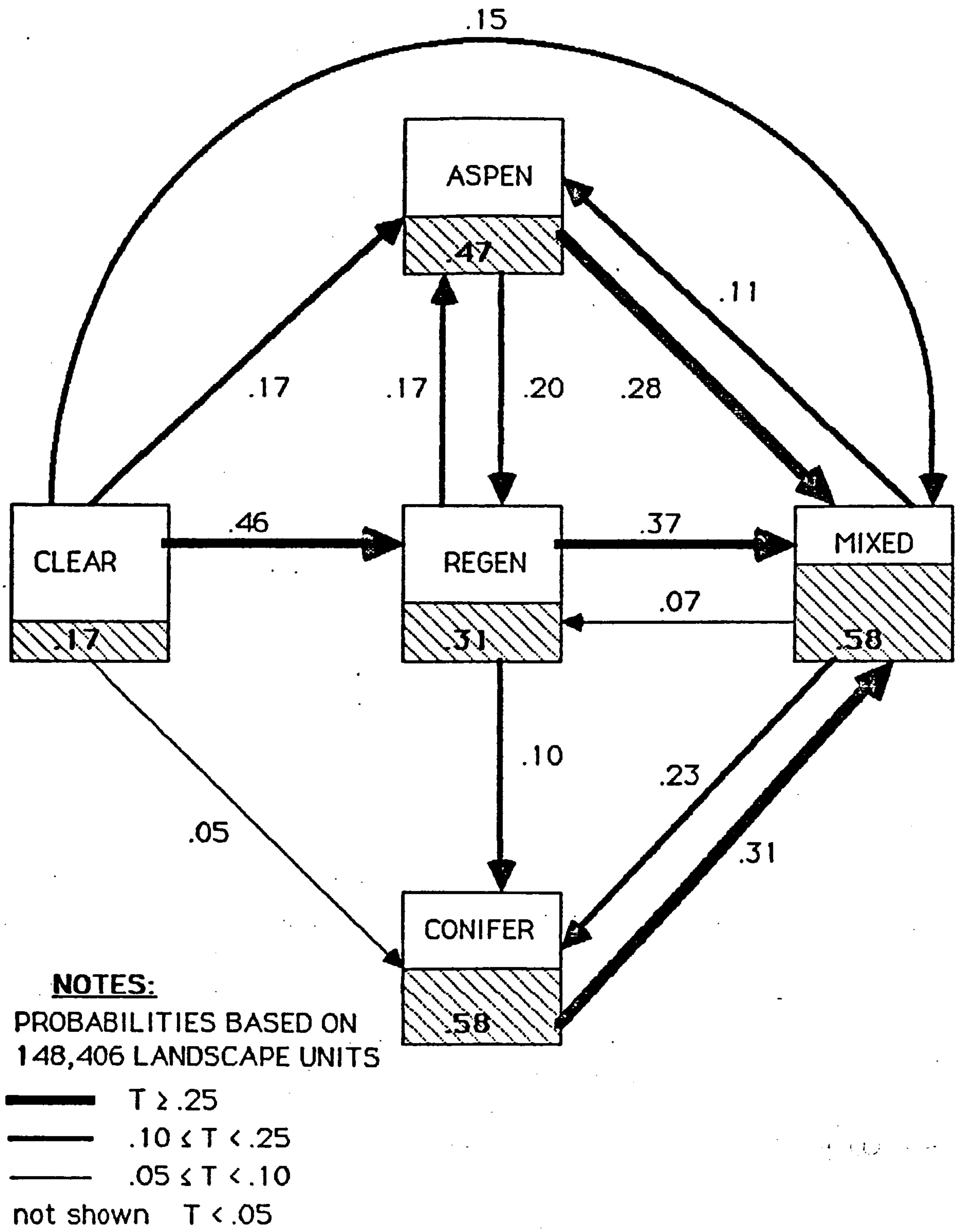
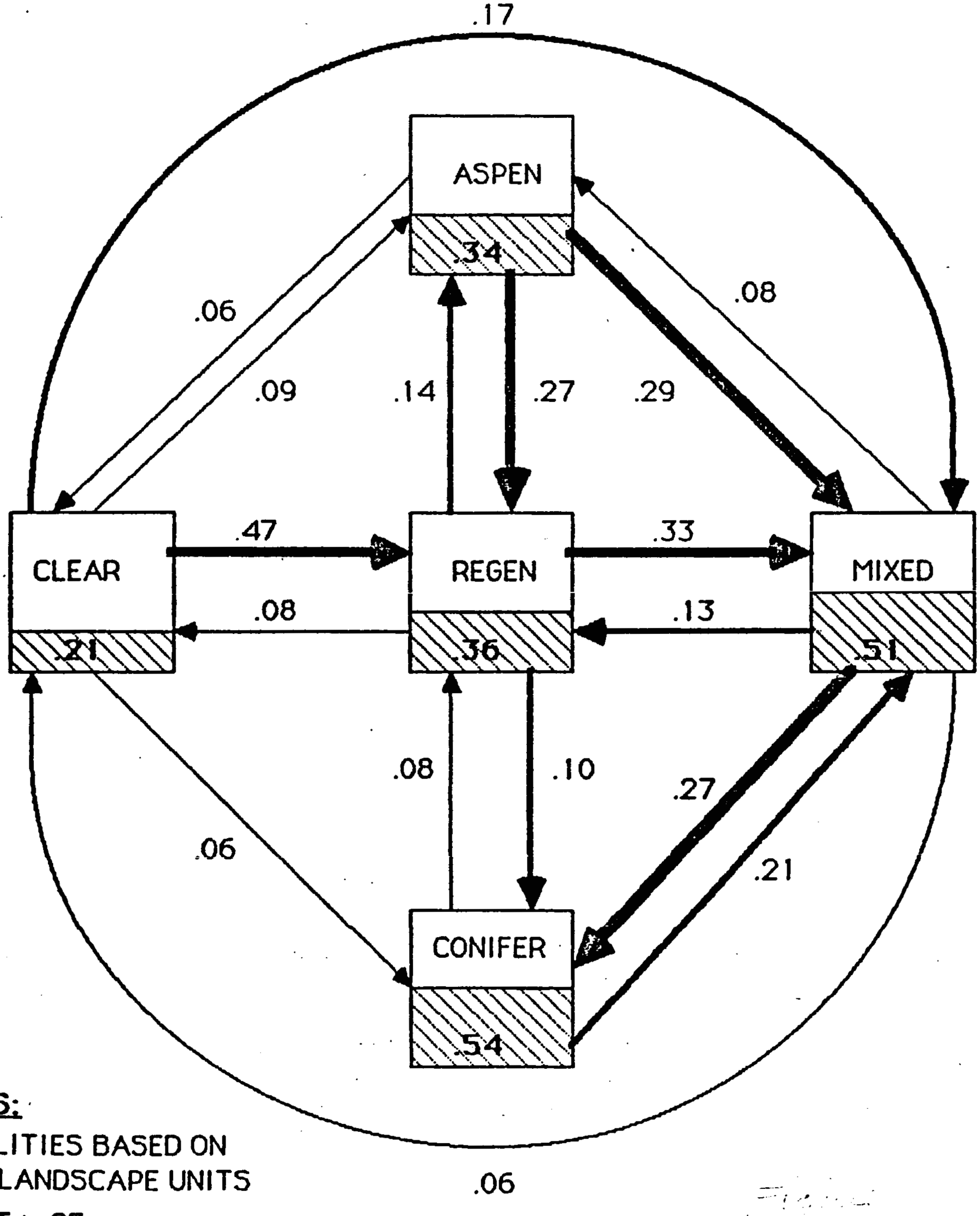
1973-83 MSS CLASSIFICATION CHANGE IMAGE
SUPERIOR NATIONAL FOREST MINNESOTA
NASA/GSFC COVER EXPERIMENT

FIGURE 1

BWCA TRANSITIONS



NON-BWCA TRANSITIONS



NOTES:

PROBABILITIES BASED ON
113,738 LANDSCAPE UNITS

(thickest line)	T ≥ .25
(medium line)	.10 ≤ T < .25
(thin line)	.05 ≤ T < .10
not shown	T < .05

TABLE 1

PERCENT OF LAND AREA BY CLASS

	1973		1983	
CLASS	WILDER-NESS	NON WILD-ERNESS	WILDER-NESS	NON WILD-ERNESS
CLEARING	3.91	8.95	1.93	7.35
REGEN.	11.2	15.23	13.4	22.2.
ASPEN	22.6	17.9	20.8	13.6
MIXED	37.9	33.5	40.6	35.4
CONIFER	24.3	21.5	26.2	21.5

TABLE 2

TRANSITION MATRIX

Rows and columns are the ecological states of the forest as measured by remote sensing. Each element in the matrix represents a transition from the 1973 state to the 1983 state. Diagonal elements are retential frequencies; off diagonal elements are transition frequencies.

(A) For an area of 534 km^2, with 148,406 landscape elements in the Protected Wilderness in the Boundary Waters Canoe Area

	1983					
1973	CLEAR-INGS	REGEN-ERATING	ASPEN	MIXED	CONIF-ER	OTHER
CLEAR-INGS	17.09	45.54	16.72	15.2	5.22	0.12
REGEN-ERATING	4.55	30.83	16.93	37.27	10.03	0.36
ASPEN	1.12	19.72	47.06	27.61	4.16	0.28
MIXED	0.52	6.81	11.28	58.11	22.55	0.72
CONIFER	1.04	4.37	1.81	31.02	57.8	3.93
OTHER	0.53	3.14	3.19	8.6	13.38	71.06

10-year Change in Forests

TABLE 2(B) For an area of 409 km², with 113,738 landscape elements in the Protected Wilderness in the Boundary Waters Canoe Area

	1983					
1973	CLEAR-INGS	REGEN-ERATING	ASPEN	MIXED	CONIF-ER	OTHER
CLEAR-INGS	20.66	47.09	9.97	17.47	4.64	0.12
REGEN-ERATING	8.18	36.39	13.71	32.71	8.84	0.14
ASPEN	5.74	26.67	34.4	28.68	4.33	0.12
MIXED	5.89	13.46	8.19	51.12	21.01	0.31
CONIFER	5.65	10.28	1.79	26.73	53.87	1.66
OTHER	3.36	16.58	12.86	23.88	16.22	26.88

April 16, 1987

TABLE 3

RECURRENCE TIMES (YEARS)[1]

	CLEARING	REGEN	ASPEN	MIXED	CONIFER
WILDERNESS	803	113	112	32	61
NON WILDERNESS	157	57	124	35	73

[1] Values are the expected average recurrence times calculated from the formula (see notes):